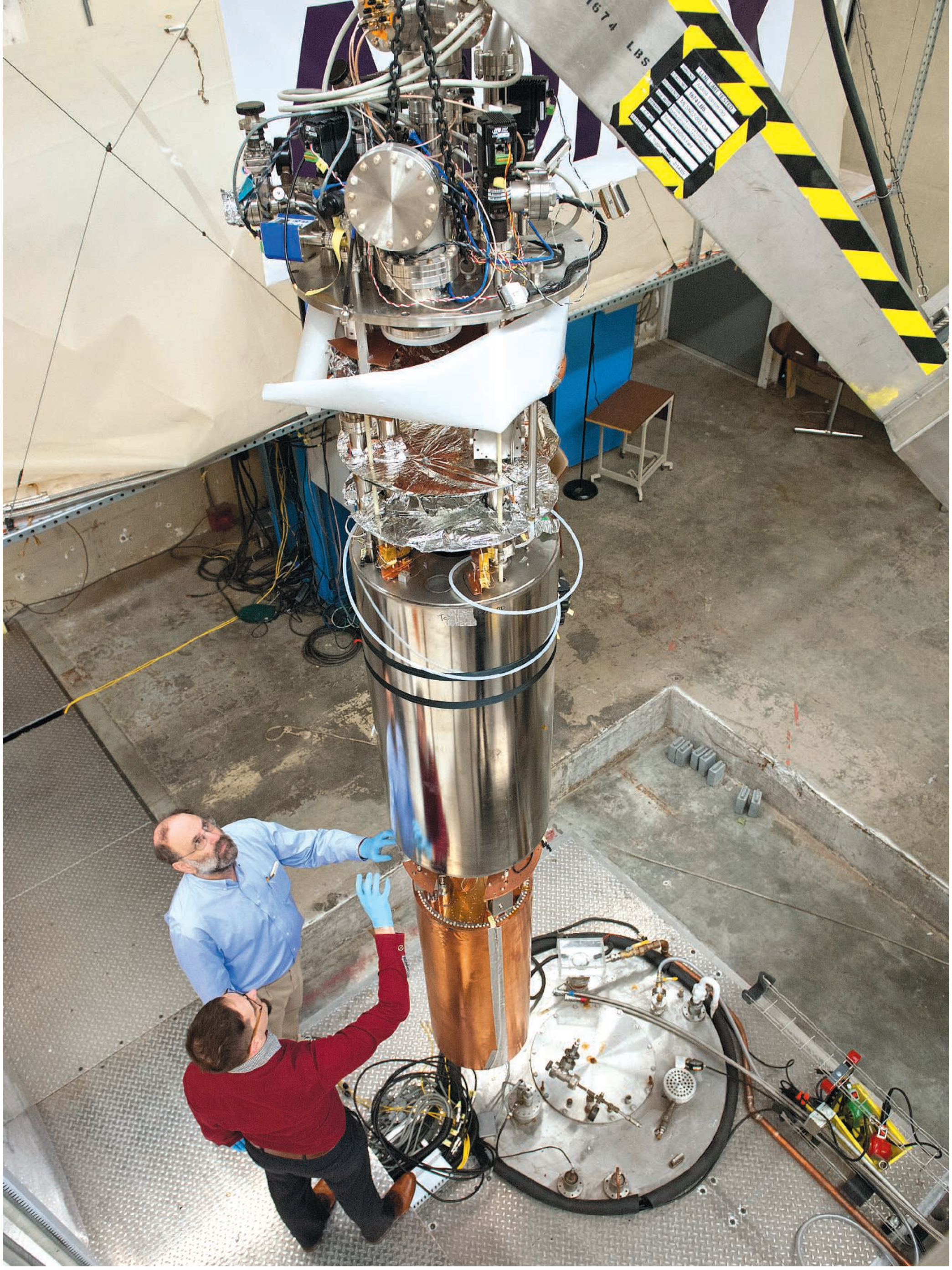

Gearing up. Gray Rybka (*front*) and Leslie Rosenberg with ADMX.

Dark Matter's Dark Horse

A rare yes/no effort promises to prove either that hypothetical particles called axions are the universe's elusive dark matter—or that they can't be

SEATTLE, WASHINGTON—In the age of the 27-kilometer-long atom smasher and the 50,000-tonne underground particle detector, the Axion Dark Matter Experiment (ADMX) hardly looks grand enough to make a major discovery. A modest 4-meter-long metal cylinder, it dangles from a wall here at the University of Washington's Center for Experimental Nuclear Physics and Astrophysics, as shiny and inscrutable as a tuna hung up for display. A handful of physicists tinker with the device, which they are preparing to lower into a silolike hole in the floor. The lab itself, halfway down a bluff on the edge of campus, is far from the bustle of the university. Yet ADMX researchers will soon perform one of the more important and promising experiments in particle physics.

Starting late this year, ADMX will search for elusive, superlight particles called axions. Predicted by nuclear theory, axions could provide the mysterious dark matter whose gravity holds the galaxies together. As a dark-matter candidate, axions have long been eclipsed by so-called weakly interacting massive particles, or WIMPs. But despite decades of searching, no one has definitively detected WIMPs, and the odds may be shifting in axions' favor. "I think there's a lot more focus on axions now because WIMPs haven't been found," says Pierre Sikivie, a theorist at the University of Florida in Gainesville and a member of the ADMX team.

ADMX isn't new. The collaboration started in 1996 at Lawrence Livermore National Laboratory in California and has made successive improvements to the experiment. The current iteration commenced in 2010, when Leslie Rosenberg, the leader of the effort, moved from Livermore to Washington, carting the experiment with him. Now ADMX researchers are about to take a crucial step. In the next few years they should achieve the sensitivity to provide a rare thing in dark-matter searches: a clear-cut yes-or-no answer.

Theory constrains the properties of axions so tightly that if ADMX researchers don't see them, then axions must *not* constitute the universe's dark matter, Rosenberg says. In contrast, a null result in a WIMP search generally sets a limit on how detectable WIMPs are but can't harpoon the basic concept. ADMX "is the only dark matter experiment I know of that can either see a candidate at a high confidence level or exclude it at a high confidence level," Rosenberg says.

Strong suspicions

Theorists didn't invent the axion to explain dark matter. Rather, they cooked it up to solve a puzzle involving the strong nuclear force, which is conveyed by particles called gluons and binds particles called quarks in trios to form the protons and neutrons in atomic nuclei. The problem is that the interplay of

CREDIT: UNIVERSITY OF WASHINGTON/MARY LEVIN quarks and gluons has a kind of symmetry not predicted by physicists' well-tested theory of the strong force.

Imagine a gaggle of quarks, antiquarks, and gluons. Swap all the particles and antiparticles and invert each particle's position and momentum. The system looks and behaves exactly as it did before—a sameness called charge-parity (CP) symmetry.

If CP symmetry didn't hold in strong interactions, the neutron would have more positive charge toward one of its magnetic poles and more negative charge toward the other. That distribution, known as an electric dipole moment, would flip with all the swapping and inverting. But experimenters have shown that, to very high precision, the neutron has no electric dipole moment. So the symmetry reigns.

That's a puzzle because according to the theory of the strong force, certain interactions among gluons ought to knock CP symmetry out of kilter. This "strong CP problem" leaves physicists with two alternatives. The parameter that sets the strength of those gluon interactions, an abstract angle called Θ, could happen to be miraculously close to zero—less than 0.0000000001. But that's the kind of "fine-tuning" physicists loathe. Or some unknown mechanism could force the offending interactions to vanish.

The axion is part of such a mechanism, which was invented in 1977 by the American theorists Roberto Peccei and Helen Quinn. They assumed that the vacuum contains a quantum field a bit like an electric field, which interacts with gluons in a way that cancels out the CP-violating interactions. In this scheme, Θ can be thought of as a marble in a circular track more or less created by the field. If the track is level, the marble can sit anywhere. But tilt the track and the marble rolls to the lowest point. The gluons and the quantum field interact in a way that always tilts the track in the direction of zero. Axions are the quantum particles associated with that field.

The scheme may sound contrived, but it resembles another famous bit of particle physics. Quarks, electrons, and other fundamental particles get their mass by interacting with a different field in the vacuum, one made up of a type of particle called the Higgs boson, which to great fanfare was discovered in 2012. Theorists have no other solution to the strong CP problem as elegant as the Peccei-Quinn mechanism, says Washington's Ann Nelson: "I'm one of the authors of the other potential solution to that problem, and I would say that the axion is more likely."

Dark matter comes as a bonus. After the big bang, different regions of the universe had different values of Θ. As the cosmos cooled, Θ in each region rolled to zero and then jiggled about that value. Such oscillations correspond to the generation of axions, in various amounts depending on how far Θ started from zero. The axions would linger today in vast numbers, making up the dark matter.

Cosmological and astrophysical observations set limits on the properties of the axion. It must have a mass of at least 1 millionth of an electron volt (1 μeV)—2 trillionths the mass of an electron. Otherwise, the infant universe would have produced so many axions that their gravity would have warped the geometry of the cosmos. Conversely, it can't be heavier than 1000 μeV, or axions would interfere with nuclear reactions and distort stellar explosions known as supernovae.

The case for the axion isn't as strong as that for the Higgs was, but some physicists says it's still so compelling that it almost has to be true. "The aesthetic arguments are very strong," says Frank Wilczek, a theorist at the Massachusetts Institute of Technology in Cambridge. "It would be a pity if it didn't exist."

Tuning into the signal

The challenge is to detect it. In principle, the task is simple. As well as feeling the strong force, axions should also interact with the electromagnetic force responsible for light and other radiation. When an axion passes through a magnetic field, it should sometimes reveal itself by turning into a photon. Given the axion's tiny mass, the photons should be low-energy radio waves. So to hunt for axions, ADMX physicists search for radio signals of a fixed frequency emanating from a strong magnetic field. "In the end, it's very much like a superfancy, very high-end AM radio, and you're just trying to find your station," says Gray Rybka, a research professor and ADMX team member at Washington.

In practice, the experiment requires a herculean effort. The chances that an axion will turn into a photon are tiny, so to have a shot at producing a signal, researchers must use a huge magnet. ADMX employs a 6-tonne superconducting coil a meter long and half a meter wide that produces a field 152,000 times as strong as Earth's field. To further enhance the signal, researchers slide inside the magnet a cylindrical "resonant cavity," in which radio waves of a specific frequency will resonate just as sound of a specific pitch resonates in an organ pipe. The cavity should amplify the production of photons 100,000-fold, and its resonant frequency can be changed by moving metal or insulating rods within it.

	Axions	WIMPs
Year invented	1977	1985
Original purpose	Solve technical problem in theory of strong nuclear force	Explain dark matter
Detectable because they	Turn into photons in strong magnetic fields	Bounce off atomic nuclei
Pros	Solve more than one problem; allow for decisive test	Flow naturally from supersymmetry; provide many models and multiple avenues of detection
Cons	Provide few models and one means of detection	Resist decisive testing; haven't shown up in decades of looking

Boosting the volume isn't enough; as much as possible, researchers also have to silence everything else. The experimental equipment itself generates random radio waves at a rate proportional to its temperature. To tamp down such "thermal noise," researchers must cool the equipment to near absolute zero. The latest incarnation of ADMX will be equipped with a liquid-helium refrigerator capable of cooling the experiment to 0.3 kelvin. Next year, researchers will go a step further and add a refrigerator that will reach 0.1 kelvin.

Temperature control is not the only problem. The amplifiers that beef up the signals generate their own ineluctable heat and noise as electrons ricochet through them. In principle, researchers could sift a signal from such noise by collecting enough data. But conven-

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tional amplifiers would require enormous "integration times."

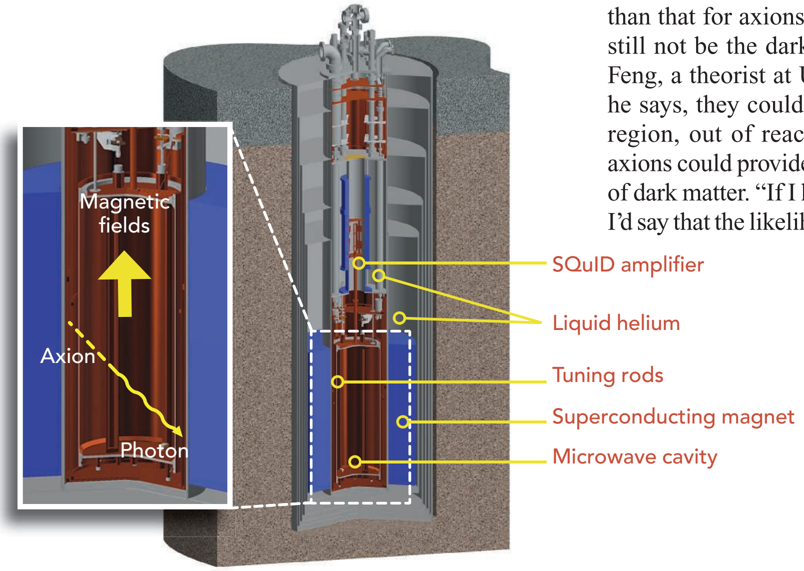
To speed things up, Rosenberg and colleagues sought help from John Clarke, a condensed matter physicist at the University of California (UC), Berkeley. Clarke is an expert on so-called superconducting quantum interference devices, or SQuIDs, tiny rings of superconducting metal that can be used, among other things, as extremely low-noise amplifiers. A SQuID's noise is set not by its temperature but by unavoidable quantum uncertainty, making it, in a sense, the quietest amplifier possible.

In 2010, the ADMX team showed that the specially designed amplifiers worked as hoped. They should make the experiment go thousands of times faster, Clarke says, "so instead of taking centuries it takes roughly 100 days." With the SQuID in place, ADMX is the most sensitive radio receiver on Earth, capable of detecting a signal with a strength of a few billionths of a billionth of a billionth of a watt, says Dmitry Lyapustin, a graduate student at Washington. "It's so powerful that if you were on Mars and you had our receiver hooked to your cell phone, you'd still get four bars," he says.

Axions may not call as soon as the physicists start taking data, which will happen by the end of the year. Over the next 3 years, they aim to work through much of the axion's potential mass range. They'll cover the low end, from 1 to 10 μeV, fairly quickly, Rosenberg predicts. The middle range, from 10 to 100 μeV, may take longer, as a heavier axion would produce higher frequency radio waves that require smaller resonant cavities. The high range, from 100 to 1000 μeV, lies out of reach of the current technology. But if nothing shows up by then, Rosenberg says, ADMX would have bagged a major result already: If the axion is that heavy, it would be too scarce to account for most of the dark matter.

Axions versus WIMPs

For a high-profile particle physics experiment, the ADMX collaboration is unusually small. It numbers about 30 researchers from seven institutions. Rosenberg says he has invited in only experts, such as Clarke, who possess essential skills. "We're very, very small because we don't need to be any bigger," he says. At the same time, much of the experiment is being built by students. For example, Lisa McBride, a graduate student at Washington, started on ADMX as an undergraduate, when she designed the gear boxes that move the cavity's tuning rods in 200-nanometer steps. Such an assignment "shows a lot of trust," she says.



Hi-fi. When an axion passes through a magnetic field, it can turn into a radio-frequency photon. ADMX aims to tune in to that radio signal, which may be a few quadrillionths of a nanowatt.

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ADMX researchers are vastly outnumbered by the many teams stalking WIMPS. These particles—no more certain than axions—interact only through the weak nuclear force, which triggers a certain type of nuclear decay. In the 1980s, theorists realized that if the infant universe spawned such particles, then just enough of them should remain to supply the dark matter, provided they weigh between one and 1000 times as much as a proton. That tantalizing coincidence is called the "WIMP miracle." Interest in WIMPs surged when theorists realized that a concept called supersymmetry, which posits for every particle known now a more massive partner, generally predicts the existence of WIMPs.

Which are more likely, axions or WIMPs? Opinions vary. As the solution to a precise technical problem, the axion is "better motivated" than the WIMP, Washington's Nelson says. Moreover, experimenters have searched for signs of WIMPs pinging off atomic nuclei with ever larger, more-sensitive detectors deep underground. Those have yet to come up with unequivocal signals, and they have gradually ruled out some of the many combinations of mass and other properties—the so-called parameter space—allowed in supersymmetric models. (As *Science* went to print, the team working with the LUX experiment at the Sanford Underground Research Facility in Lead, South Dakota, was preparing to release the results of the most sensitive WIMP search yet; see p. 542.) So the WIMP miracle "is looking a little frayed these days," Wilczek says.

Still, some theorists find the case for WIMPs as the dark matter more compelling than that for axions. Axions could exist and still not be the dark matter, notes Jonathan Feng, a theorist at UC Irvine. For example, he says, they could fall in that higher mass region, out of reach for ADMX, in which axions could provide no more than a smidgen of dark matter. "If I had to put a number on it, I'd say that the likelihood that the axion solves the strong CP problem is 90%, but the chances that the axion is the dark matter is 10%," Feng says. He argues that roughly half the parameter space for WIMPs remains viable.

Whatever ADMX sees, it will tell physicists something important. A null result would skewer the axion as a dark-matter candidate, Rosenberg says. Some theorists, however, expect the death rattle to come slowly. Die-hards would just concoct more contrived models to explain why the axion wasn't seen, says Marc Kamionkowski, a theorist at Johns Hopkins University in Baltimore, Maryland. "A theory is only dead when everybody agrees it's dead," he says.

For example, Nelson says, theorists already know one way to dodge the lower limit on the axion's mass without producing more dark matter than astrophysicists observe. Cosmologists think that in the first instants after the big bang, the universe underwent a growth spurt called inflation, in which space expanded at greater than light speed. Axions emerged after inflation, theorists assume. But if axions emerged before inflation, all of the universe we can see could have started out as a tiny patch in which the density of axions happened to be very low. That just-so story would allow axions to be abundant on a cosmic scale and light enough to elude ADMX.

Or ADMX might just hear the faint radio whisper of passing axions. Rosenberg says he'd be surprised if the particles didn't show up. "We're true believers," he says. To build such an intricate, sensitive experiment, he says, "I think you have to be."

–ADRIAN CHO

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